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THESIS

A DISPERSION MODEL FOR HEATED EFFLUENT
FROM AN OCEAN OUTFALL

by

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from an Ocean Outfall

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ABSTRACT

A mathematical model is developed for dispersion of a heated effluent from an ocean outfall. Input parameters include atmospheric and oceanic conditions and discharge characteristics. The model solves the steady-state, two-dimensional differential equation for non-conservative diffusion of heat in a moving fluid. The solution is calibrated and verified using data from surveys conducted at the Southern California Edison Company power plant at Huntington Beach, California. Temperature fields predicted by the model are compared with the actual fields for seven different surveys. These comparisons indicate that the model can be used to predict the large scale influence of the outfall on the local ocean environment.

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LIST OF SYMBOLS USED

c_p = Specific heat

e_a = Vapor pressure of air (mb)

e_w = Saturated vapor pressure (mb)

h = Cloud height in thousands of feet

qo = Excess heat added by the effluent

Dx = Diffusion coefficient in x-direction

Dy = Diffusion coefficient in y-direction

Hw = Reference depth of the temperature field

Pa = Atmospheric pressure (mb)

Q = Net gain or loss of heat by a system

Qb = Effective back radiation

Qe = Heat loss owing to evaporation

Qh = Heat conduction across interface

Qr = Reflected radiation

Qs = Insolation

T or

Tw = Sea surface temperature

Ta = Air temperature

Te = Equilibrium sea surface temperature

To = Temperature at the boil

$T\infty$ = Ambient sea surface temperature

U = Current in the x-direction

V = Current in the y-direction

W = Wind speed (kts)

Φ = Latitude minus solar declination

ρ_0 = Density of the water

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I. INTRODUCTION

A. GENERAL

The existence of a low temperature heat sink for cooling water is of extreme importance to the efficiency of steam power plants. Since the ocean is, in effect, an infinite fluid heat sink, power companies find it desirable to locate their plants on the coast to utilize the ocean waters as condenser coolant.

Steam electric power plants circulate large quantities of cooling water through their condensers to extract excess waste heat from the steam leaving the low pressure side of their turbines. The quantity of waste heat produced is a function of the size and efficiency of the power plants. The size and number of these plants are increasing, particularly those using nuclear fuel. Nuclear power plants are even less efficient in their utilization of heat than fossil fueled power plants. This is because technological difficulties make it impractical, uneconomical, or unsafe to produce high-pressure, superheated steam in a water-cooled reactor system which would allow more efficient operation [Ref. 25].

Due to the large heat capacity of the ocean, the mean ocean temperature will not be significantly affected by the introduction of this waste heat. Local temperatures, however, may be greatly affected and care must be taken to minimize any adverse effects on the environment. Hence it is highly desirable to develop a model that adequately predicts the temperature distribution and the area of influence of the waste heat. The results of such a model could enable estimates to be made of the influence of the outfall on marine flora and fauna, and also aid in planning the location of the cooling water intake so that recirculation can be kept to a minimum.

B. EFFECTS OF THERMAL POLLUTION

Ecologists consider temperature the primary control of life on earth. Each aquatic species becomes adapted to the seasonal variations in the temperature of the water in which it lives but it cannot adjust to the shock of an abnormally abrupt change [Ref. 8]. In addition to direct mortality from a temperature change, there may be indirect changes. For example, temperatures which are not lethal themselves may affect metabolism, reproduction, longevity and growth, as well as increasing or decreasing important food organisms. For these reasons there is growing concern among ecologists about the heating of aquatic habitats by man's activities.

In an ocean outfall several detrimental effects could occur. The ecosystem could be upset by hot waste water to the extent that a vital link in the food chain could disappear, increase in abundance, or be replaced by another organism. If this occurred, there could be an increase or decrease in game fish and/or an increase in other less desirable species. Historically, it is known that in the summer, Macrocystis (giant kelp) plants in the San Diego area suffer from prolonged exposure to warm surface waters and as a result "die-back". They regenerate quickly with the arrival of cooler surface water in the fall [Ref. 17]. Not only is kelp harvested commercially, but it is a haven for many marine species. The influence of a hot effluent could prevent the regeneration of kelp and its disappearance could completely upset the ecology in the area of the outfall. There is an additional problem where a cooling water outfall is in the vicinity of a sewage outfall. Oxygen and sunlight are important in neutralizing sewage. The presence of warmer water not only limits the amount of dissolved oxygen, but also the warm water may be less dense and override the sewage cutting off its access to the atmosphere.

Beneficial uses of a heated effluent are also possible and should be more fully explored. Presently, there are desalinization plants built or planned in conjunction with power plants that use the waste heat in their operation. An increase in temperature along a section of beach may make it more desirable as a recreation area. Longshore currents inside the surf zone could carry the heat excess over a long section of coastline. Coolant water could further be used on a varying basis to control the temperature in a limited area to allow fish farming or aquaculture.

C. BACKGROUND

A model to predict the dispersion of a heated effluent from an ocean outfall should include all the physical and thermal processes that actually act on the effluent. Among the processes and features that should be included are the volume and temperature of the discharge; the size, depth and orientation of the discharge opening; the thermal and saline structure of the ambient receiving water; the currents; the waves; the exchange of energy across the air-sea interface; horizontal and vertical diffusion; and possibly topography.

The heated coolant water, being less dense than the ambient sea water, rises with considerable momentum. The column of heated water entrains cooler water and is diluted as it rises [Ref. 1]. If the effluent reaches the surface, it spreads out as a thin, warm layer [Ref. 23]. The strong temperature gradient between the thin layer of warm water and the cooler receiving water inhibits vertical mixing, and dispersion of the warm effluent is primarily horizontal. In the presence of a current the surface isotherms are roughly elliptical; the ratio of major to minor axis being a function of current speed - the patch being elongated in the direction of flow. Usually there is quite a bit of irregularity in the observed isotherms, which may be attributed to a number of phenoma including random current motion, internal waves, and upwelling or downwelling.

In a classical study of outfall polluting, Rawn and Palmer [Ref. 18] discharged jets of colored water into sea water in the field through nozzles of various sizes and orientations. From these experiments, they were able to establish empirical equations relating field thickness to the depth at which the outfall is located, the radius of the top of the jet to both the depth of the outfall and the diameter of the outlet, and dilution to the distance from the outfall. Edinger and Geyer [Ref. 11], employing temperature data collected at several locations in an embayment over a five month period, obtained a solution for temperature distribution which involved the following parameters: plant pumping rate, exchange of heat with the atmosphere, and apparent diffusivity in both upstream and downstream directions. Their solution neglects any ambient current and is based on the assumption that the embayment waters are uniformly mixed in the vertical and cross channel directions. Wada [Refs. 27 and 28] describes the effect of various factors on the recirculation of cooling water in a bay. He also presents a theory from which quantitative prediction of water temperature and velocity fields may be obtained for a bay using numerical techniques. Pritchard and Carter [Ref. 6] predicted the temperature distribution from a proposed river outfall by using a fluorescent dye tracer to analyze the physical processes of advection and diffusion. A correction for the non-conservative nature of heat was applied in the solution. The buoyancy of the heated effluent was treated as an unknown and solutions were presented for several different depths of influence of heat.

Silberman and Stefan [Ref. 21] used a hydraulic model to predict the effects of an outfall on water temperature in a lake. In another lake study Hoppes, Zeller and Rohlich [Ref. 26] conducted field studies throughout an entire year to assist in their development of a model to predict heat dissipation and induced circulation from surface outfalls. Other noteworthy research in these areas is contained in References [5], [9], [10], [13], and [15].

In this study, a mathematical model has been developed for heat dispersion from an outfall in an open coastal area. The techniques and conclusions are designed to have general application but are specifically based on part of a continuing survey that was conducted by Marine Advisors, an oceanographic consulting firm, for Southern California Edison Company, in the waters adjacent to the power plant located at Huntington Beach, California [Refs. 16 and 17]. This survey includes information on physical oceanographic conditions, marine flora and fauna, fish catches, bottom sediments and suspended fine sediments as well as temperature distribution.

The Huntington Beach power plant withdraws and discharges its condenser cooling water through two large pipes, each terminating in the ocean at depths of about 34 feet and 28 feet respectively. They are located approximately 1500 feet from the beach. The slope of the bottom in the area of the outfall is about 1/50.

II. HEAT BUDGET

A. GENERAL

The distribution of temperature in a body of water resulting from a discharge of warm effluent is influenced by the characteristics of the effluent itself, and by the external mechanisms which control the exchange of heat with the surroundings or environment. The air-sea interface processes are jointly referred to as the heat budget which can be expressed as:

$$Qs - Qr - Qb - Qh - Qe = Q \tag{2-1}$$

where Qs is the incident flux of short-wave radiant energy from the sun through the water surface, Qr is solar radiation reflected at the sea surface, Qb is the net energy lost by the body of water through the exchange of long-wave radiation between the atmosphere and the body of water, Qe is the energy loss associated with evaporation, Qh is the exchange between the body of water and the atmosphere in the form of sensible heat, and Q is the net gain or loss of heat in the body of water. Conduction of energy through the bottom, heating due to chemical and biological processes, and the transformation of kinetic energy into thermal energy are generally neglected because of their small magnitude.

In the present study an analytical solution is sought and hence it was necessary to express the total heat energy exchange across the air-sea interface as a linear function of sea surface temperature for a given set of atmospheric conditions:

$$Q = A - BTw. \tag{2-2}$$

In order to adhere to this restriction the individual components of the heat budget were linearized. Each mechanism and the procedure followed to compute its contribution are considered separately. The results are summed to get the total exchange.

B. SOLAR RADIATION

The solar radiation (Qs) is a function of the sun's altitude and the cloud cover. Laevastu [Ref. 14] presents several empirical formulae for estimating insolation including nomographic aids for their evaluation. Reflected radiation (Qr) is primarily a function of the sun's altitude and cloudiness although the state of the sea probably plays a minor part. Laevastu treats Qr as a function of Qs. James [Ref. 3] combines Qs and Qr in a term he calls effective insolation (Qs - Qr) and presents nomograms for its determination. Effective insolation was computed using Figure 1 and Tables II and III from James [Ref. 3]. The latitude at the data site is 34° North. The values for the sun's declination and duration of sunlight were interpolated from Table II. A value Φ is defined as latitude minus solar declination. The cloud category is based on Lumb's Cloud Classification (Table III) and the cloud conditions given in Refs. [7] and [24]. The effective insolation for the day was obtained by entering Figure 1 with the value of Φ, proceeding to the appropriate cloud category, then vertically to the proper number of hours of daylight and finally moving horizontally to the right. The effective insolation per hour, for purposes of this study, was taken to be 1/24 of this daily value. Although this average value is not a true value for most of the data periods, it was felt that because of lag time in the effects of insolation it was an adequate value.

Since this value is a constant with respect to sea surface temperature it easily fits the linear restriction.

C. EFFECTIVE BACK RADIATION

The effective back radiation (Qb) can be estimated by treating the water surface as a gray-body emitter where it is some function of the fourth power of the sea surface temperature. One of the more popular formulae used is that developed by Anderson [Ref. 2].

$$Qb = (4.75 \times 10^{-9})\ Tw^4\ (1-a+be_a) \qquad (2\text{-}3)$$

where $a = 0.74 + 0.025Ce^{-0.0584h}$

$b = 0.0049-0.00054Ce^{-0.060h}$

e_a = Vapor pressure of air (mb)

C = Cloud amount in tenths

h = Average cloud height in thousands of feet.

To expedite the use of Anderson's equation, James [Ref. 3] prepared a nomograph for a normal range of values (Fig. 2). Cloud height and cover are expressed in terms of Lumb's Cloud Category. Figure (2) was entered using sea surface temperature. By proceeding horizontally to the atmospheric vapor pressure and moving vertically to the cloud cover, then horizontally to the right, the value of effective back radiation was found. By doing this for several temperatures in the range of observed values and plotting the results it was possible to linearize the effective back radiation as a function of sea surface temperature.

D. EVAPORATION

Formulae for computing evaporation vary from simple expressions relating evaporation to vapor pressure differences and wind speed alone, to complex considerations involving aerodynamic surfaces, the occurrence of spray, and the vertical profile of wind and vapor pressure. Laevastu [Ref. 14] concluded that a modification of the formula of Rohwer [Ref. 20] is the best available for computation of evaporation from the sea surface. The formula as modified is:

$$Qe = 2.46\,(0.26 + 0.04W)\,(e_w - e_a) \tag{2-4}$$

where e_w = Saturated vapor pressure at sea surface temperature

W = Wind speed in knots.

The case where e_a is greater than e_w produces condensation and a heat gain by the water. However, this is a rather rare occurrence in mid latitudes. The above formula was used to compute Qe. Since e_w is the variable, it was necessary to use another of James' nomograms (Fig. 3). By entering the abscissa with sea surface temperature (Tw) and rising vertically to the diagonal line, e_w was found by interpolating between the e_a lines. By using the same procedure described in the previous paragraph, it was possible to linearize e_w as a function of Tw over the limited range of observed values of sea surface temperature. By substituting this linear function for e_w into the above formula, the energy loss caused by evaporation was computed as a function of sea surface temperature.

E. SENSIBLE HEAT

Sensible heat transfer Qh is a function of the vertical temperature gradient and the degree of turbulence or eddy conductivity above the sea surface. Because of the lack of information on the eddy conductivity, it is general practice to relate sensible heat transfer to evaporation. Assuming that evaporation and conduction of specific heat are similar processes, Bowen [Ref. 30] derived the following ratio for the two processes:

$$\frac{Qh}{Qe} = R = K \frac{(Tw - Ta)}{(e_w - e_a)} \cdot \frac{Pa}{1000} \qquad (2\text{-}5)$$

where R = Bowen ratio

Pa = Atmospheric pressure (mb)

K = Constant approximately 0.61 under normal conditions.

Neglecting the pressure term which has only a small effect, and substituting for Qe in the above equation, the transfer of sensible heat can be expressed as:

$$Qh = 0.83\ (0.26 + 0.04W)\ (Tw - Ta). \qquad (2\text{-}6)$$

This equation is applicable where colder air overlies warmer water. For the reverse situation stability reduces the transfer of heat and according to Laevastu [Ref. 14] the appropriate relation is:

$$Qh = 0.036W\ (Tw - Ta). \qquad (2\text{-}7)$$

The cases where Ta is greater than Tw are not numerous and in light of the small relative magnitude of Qh, it is felt that equation (2-6) is a good approximation. Since this equation is already a linear function of water temperature, no further manipulation is necessary. James [Ref. 3] has plotted a nomograph for finding latent and sensible heat transfer based on the above equations (Fig. 4).

The sum of all the above individual linear functions of sea surface temperature is the total heat transfer across the air-sea interface and may be expressed as:

$$Q = A - BT.$$

The subscript has been dropped since only water temperatures will be discussed from this point.

An equilibrium temperature, Te, can be defined such that, for T equal to Te, Q is equal to zero. As will be shown later in the development of the model, a steady state condition is assumed. For steady state conditions to exist, the ambient sea temperature must equal the equilibrium temperature. Hence the constant A is modified such that:

$$A - BT_\infty = 0 \quad \text{or} \quad A = BT_\infty$$

where T_∞ = Ambient sea temperature.

This in effect neglects the seasonal heating and cooling of the ocean.

III. MODEL DEVELOPMENT

A. GENERAL

The general steady-state heat equation for an advective system can be written:

$$u_i \frac{\partial T}{\partial x_i} - \frac{\partial}{\partial x_i}\left(D_i \frac{\partial T}{\partial x_i}\right) = Q\ (T) \tag{3-1}$$

where i=1,2,3 corresponds to the x,y,z direction respectively and repeated indices imply summation. u_i represents the velocity component. D_i is the eddy diffusion coefficient for heat. Q(T) accounts for any heat gain or loss by the system and may be expressed as a function of temperature. This allows for a non-conservative system in which heat is allov to be lost or gained from the body of the fluid. This equation assumes the mean heat flux is proportional to the negative temperature gradient (heat flows from high heat to low heat) where the proportionality factor D_i is the diffusion coefficient. This is the so called Fickian diffusion where

$$\overline{u_i'T'} = D_i \frac{\partial T}{\partial x_i} \tag{3-2}$$

u_i' refers to the turbulence component of velocity, T' refers to the turbulent temperature fluctuation, and the over bar signifies a time mean average.

B. ASSUMPTIONS

In order to obtain an analytical solution for the heat equation it is necessary to idealize the physical situation to make the mathematics more tractable. The following simplifying assumptions will be made in the derivation of the proposed model.

1. Only a uniform mean oceanic longshore current will be considered. Additional velocity resulting from the volume discharge of the outfall will be neglected. This is reasonable since the outfall only affects current to a measurable degree in the immediate vicinity of the boil. The velocity is also assumed uniform over depth in the diffusing layer. To simplify the development, the x-axis will always conform to the direction of flow, although the results could easily be extended to a more general formulation of the currents.

2. A two layered system separated at a reference depth is considered. There is complete vertical mixing assumed in the top layer and no mixing between the two layers. This closely resembles the thermal structure found in shallow coastal water in which the upper layer is rather thoroughly mixed by wind and wave action and diurnal heating and cooling. A steep, well-developed thermocline is typical of summer conditions in the temperate zone under consideration. The water beneath the thermocline tends to be isothermal. The steep thermocline tends to inhibit vertical mixing. Wada [Ref. 28] found that the horizontal thermal diffusivity is 50 times greater than the vertical thermal diffusivity. Therefore it is reasonable to assume that the reference depth, once established, can be assumed to be a constant throughout the horizontal field.

3. As already mentioned, the ambient sea temperature is assumed equal to the equilibrium sea temperature, and the heat budget is assumed a linear function of temperature.

4. A steady-state situation exists.

5. The horizontal diffusion coefficients are constants. This assumption greatly simplifies solving of the differential equation.

Although investigations have been made into the dependency of the diffusion coefficients on distance from the source and velocity components, none of the results have gained universal acceptance.

6. All boundary effects except for the surface will be neglected. The development assumes an infinite expanse of water of constant depth. This means that the coastline, shoaling bottom and surf zone are ignored.

7. The outfall will be treated as a line source in accordance with the two dimensional assumption. This is a fairly realistic assumption as compared to the actual observations.

C. DEVELOPMENT

Incorporating the above assumptions, the governing equation reduces to the two-dimensional, steady-state equation for diffusion of heat in a moving fluid:

$$U \frac{\partial T}{\partial x} - Dx \frac{\partial^2 T}{\partial x^2} - Dy \frac{\partial^2 T}{\partial y^2} = \frac{Q}{\rho_o c_p Hw} \qquad (3\text{-}3)$$

where $U(x)$ = Mean current (along x-axis)

Q = Net gain or loss of heat across the surface

Dx = Diffusion coefficient in x-direction

Dy = Diffusion coefficient in y-direction

ρ_o = Density of fluid, a constant

c_p = Specific heat of the fluid

Hw = Specified reference depth.

The first term of the equation represents advective heat transport, the next two terms, the thermal diffusion across the temperature gradients, and the right hand term, loss of heat across the air-sea interface.

The problem will be attacked by making a number of simple transformations in order to reduce the differential equation to a more recognizable form having a known solution. To remove the coefficient from the diffusion terms, two new variables are defined.

$$\sigma = \frac{x}{Dx^{1/2}}, \quad \eta = \frac{y}{Dy^{1/2}}$$

then

$$\frac{\partial T}{\partial x} = \frac{1}{Dx^{1/2}} \frac{\partial T}{\partial \sigma},$$

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{Dx} \frac{\partial^2 T}{\partial \sigma^2}, \tag{3-4}$$

and

$$\frac{\partial^2 T}{\partial y^2} = \frac{1}{Dy} \frac{\partial^2 T}{\partial \eta^2}.$$

The transformation to the (σ, η) plane simplifies the equations to describing homogeneous dispersion of heat.

Substituting these partial derivatives, (3-3) reduces to

$$\frac{U}{Dx^{1/2}} \frac{\partial T}{\partial \sigma} - \frac{\partial^2 T}{\partial \sigma^2} - \frac{\partial^2 T}{\partial \eta^2} = \frac{Q}{\rho_o c_p Hw}. \tag{3-5}$$

As previously stated, Q is assumed to be a linear function of sea surface temperature. Letting $Q = A - BT$ and also letting $A' = \frac{A}{\rho_o c_p Hw}$, $B' = \frac{B}{\rho_o c_p Hw}$, and $U' = \frac{U}{Dx^{1/2}}$ (3-5) becomes

$$U' \frac{\partial T}{\partial \sigma} - \frac{\partial^2 T}{\partial \sigma^2} - \frac{\partial^2 T}{\partial \eta^2} = A' - B'T. \tag{3-6}$$

To eliminate A', another new variable is defined

$$T' = \frac{T - T\infty}{To - T\infty} \text{ or } T = T' (To - T\infty) + T\infty \tag{3-7}$$

where To = Outfall (boil) temperature

$T\infty$ = Ambient temperature = Equilibrium temperature.

Then

$$\frac{\partial T}{\partial \sigma} = (To - T\infty)\,\frac{\partial T'}{\partial \sigma}\,,$$

$$\frac{\partial^2 T}{\partial \sigma^2} = (To - T\infty)\,\frac{\partial^2 T}{\partial \sigma^2}\,, \qquad (3\text{-}8)$$

and

$$\frac{\partial^2 T}{\partial \eta^2} = (To - T\infty)\,\frac{\partial^2 T'}{\partial \eta^2}\,.$$

Substituting these partial derivatives into (3-6) so that

$$U'\,(To - T\infty)\,\frac{\partial T'}{\partial \sigma} - (To - T\infty)\left(\frac{\partial^2 T'}{\partial \sigma^2} + \frac{\partial^2 T'}{\partial \eta^2}\right) = A' - B'\left[T'\,(To - T\infty) + T\infty\right]. \qquad (3\text{-}9)$$

Simplifying this equation,

$$U'\,\frac{\partial T'}{\partial \sigma} - \left(\frac{\partial^2 T'}{\partial \sigma^2} + \frac{\partial^2 T'}{\partial \eta^2}\right) = \frac{A' - B'T\infty}{To - T\infty} - B'T'\,. \qquad (3\text{-}10)$$

But since it was assumed $A - BT\infty = 0$ it follows that $A' - B'T\infty = 0$ and the equation becomes

$$U'\,\frac{\partial T'}{\partial \sigma} - \left(\frac{\partial^2 T'}{\partial \sigma^2} + \frac{\partial^2 T'}{\partial \eta^2}\right) = -B'T' \qquad (3\text{-}11)$$

Now consider the transformation from a stationary to a moving coordinate system. Defining another new variable

$$\xi = \sigma - U't \qquad (3\text{-}12)$$

where t is an arbitrary time variable.

Then $\frac{\partial \xi}{\partial \sigma} = 1$ and $\frac{\partial t}{\partial \sigma} = 0$ so that

$$\frac{\partial T'}{\partial \sigma} = \frac{\partial T'}{\partial \xi}\frac{\partial \xi}{\partial \sigma} + \frac{\partial T'}{\partial t}\frac{\partial t}{\partial \sigma} = \frac{\partial T'}{\partial \xi}$$

and (3-13)

$$\frac{\partial^2 T'}{\partial \sigma^2} = \frac{\partial^2 T'}{\partial \xi^2} .$$

Substituting these partial derivatives in (3-11)

$$U' \frac{\partial T'}{\partial \xi} - \left(\frac{\partial^2 T'}{\partial \xi^2} + \frac{\partial^2 T'}{\partial \eta^2}\right) = - B'T'. \tag{3-14}$$

To integrate this equation, let

$$T = \Phi\ (\xi,\ \eta)\ e^{U'\xi/2} \tag{3-15}$$

in which Φ is an undetermined function. This transformation effectively removes the advection term.

Then

$$\frac{\partial T'}{\partial \xi} = e^{U'\xi/2}\frac{\partial \Phi}{\partial \xi} + \frac{\Phi U'}{2} e^{U'\xi/2} \tag{3-16}$$

$$\frac{\partial^2 T'}{\partial \xi^2} = e^{U'\xi/2}\frac{\partial^2 \Phi}{\partial \xi^2} + U'e^{U'\xi/2}\frac{\partial \Phi}{\partial \xi} + \frac{\Phi (U')^2}{4} e^{U'\xi/2}$$

and

$$\frac{\partial^2 T'}{\partial \eta^2} = e^{U'\xi/2}\frac{\partial^2 \Phi}{\partial \eta^2} .$$

Substituting these partial derivatives in (3-14) and simplifying,

$$\left[\frac{(U')^2}{4} + B'\right]\Phi - \left(\frac{\partial^2 \Phi}{\partial \xi^2} + \frac{\partial^2 \Phi}{\partial \eta^2}\right) = 0. \tag{3-17}$$

To further simplify, let $\frac{(U')^2}{4} + B' = k^2$. Reversing the signs, the equation can now be written:

$$\left(\frac{\partial^2 \Phi}{\partial \xi^2} + \frac{\partial^2 \Phi}{\partial \eta^2}\right) - k^2\Phi = 0. \tag{3-18}$$

This transformed equation defines a new temperature field, Φ in a moving plane in which the advection term has been removed and Φ is being diffused and decayed radially. Hence, it is convenient to work in cylindrical coordinates with Φ (r, θ) where $\xi^2 + \eta^2 = r^2$ and $\theta = \tan^{-1}(\eta/\xi)$. This transformation is immediately written down as

$$\frac{\partial^2\Phi}{\partial r^2} + \frac{1}{r}\frac{\partial\Phi}{\partial r} + \frac{1}{r^2}\frac{\partial^2\Phi}{\partial\theta^2} - k^2\Phi = 0, \tag{3-19}$$

but since in this case the transformed temperature field is symmetrical about $r = 0$, the function Φ must satisfy the simpler total differential equation:

$$\frac{d^2\Phi}{dr^2} + \frac{1}{r}\frac{d\Phi}{dr} - k^2\Phi = 0. \tag{3-20}$$

D. SOLUTION

The differential equation above is recognized as a Bessel form having the general solution [Ref. 22]

$$\Phi = C_1\, J_o(kir) + C_2\, Y_o(kir), \tag{3-21}$$

or in terms of the modified Bessel functions and re-expressed in T,

$$T = (To - T\infty)\, e^{U'\xi/2}\left[C_1\, I_o(kr) + C_2\, K_o(kr)\right] + T\infty. \tag{3-22}$$

The above general solution must satisfy the far field (asymptotic) boundary condition,

$$T \longrightarrow T\infty \text{ and } r \longrightarrow \infty. \tag{3-23}$$

It can be shown that of the two functions I_o and K_o, only K_o will satisfy this condition. Accordingly, $C_1 = 0$ and

$$T = (To - T\infty)\, e^{U'\xi/2}\left[C_2\, K_o(kr)\right] + T\infty. \tag{3-24}$$

To solve for C_2 the rear field boundary condition,

$$- DX\ (2\pi r) \frac{dT}{dr} = \frac{qo}{Hwc_p \rho_o} \text{ as } r \longrightarrow 0 \qquad (3\text{-}25)$$

is applied. This condition expresses the fact that the rate at which excess heat is added by the effluent, qo, is equal to the diffusive transport of heat radially outwards near the axis $r = 0$. Here it is assumed that as $r \longrightarrow 0$, diffusion is constant in all directions and Dx represents the diffusion coefficient. Advection is neglected very near the source This in effect neglects the conservation of mass from the volume discharge, and leads to an invalid solution in the immediate vicinity of the outfall. Although this appears to be an unrealistic boundary condition, in practice it does not seem to be any great limitation. By applying the above boundary condition it is found that;

$$C_2 = \frac{qo}{2\pi HwDx}\ (To - T\infty) \qquad (3\text{-}26)$$

and the solution becomes:

$$T = e^{U'\xi/2} \frac{qo}{2\pi HwDx}\ K_o(kr) + T\infty. \qquad (3\text{-}27)$$

Reversing the previous simplifications and transformations the solution can be written:

$$T = e^{U(x-Ut)/2Dx} \left(\frac{qo}{2\pi HwDx}\right) K_o \left[\left(\frac{U^2}{4Dx} + \frac{B}{\rho_o c_p Hw}\right)^{1/2} \left(\frac{(x-Ut)^2}{Dx} + \frac{y^2}{Dy}\right)^{1/2}\right] + T\infty$$

$$(3\text{-}28)$$

The above solution represents a steady-state, non-conservative dispersion model for heated effluent from an ocean outfall treated as a line source. The behavior of the solution can be examined by considering the components of the solution. The exponential term increases in the downstream direction and decreases in the upstream direction. This represents the influence of advection and is the term in which the current makes its largest contribution to the solution. The Bessel function term represents the radial diffusion of heat and the temperature field decay. The combination of the two terms plus the constant represent the difference between the temperature and the ambient temperature. The temperature unrealistically goes to infinity at the source, but the solution was not expected to be valid in the immediate vicinity of the boil. For downstream values of x, the exponential and Bessel function terms vary inversely with each other; the Bessel function term decreases at a slightly greater rate than the exponential term increases resulting in a decrease in temperature with distance. In the upstream direction as the distance increases both terms approach zero and the temperature approaches the ambient temperature more rapidly.

IV. MODEL APPLICATION

The model was calibrated and verified using the data from the Huntington Beach power plant. The temperature and current surveys [Refs. 16 and 17] were conducted at the different tidal conditions listed below during the late summer and early fall of 1963 and 16 February 1965 as follows:

26 July 1963 27 July 1963	A period of small diurnal and small semi-diurnal tidal components.
16 August 1963 17 August 1963 16 February 1965	Periods of large diurnal and large semi-diurnal tidal components.
28 August 1963	A period of large diurnal and small semi-diurnal tidal components.
4 October 1963	A period of small diurnal and large semi-diurnal tidal components.

The measurements were generally made only during daylight hours. Temperature-measuring instruments used on these surveys were a conventional bathythermograph (MBT), an electronic bathythermograph which is capable of being towed at fixed depths as well as being lowered vertically, bucket thermometers and an airborne radiation thermometer. Current measurements were made by placing drogues in the vicinity of the outfall and tracking their progress. The discharge temperature, discharge volume, and meteorological data were obtained from the Southern California Edison Company. Additional meteorological data were obtained from the City of Huntington Beach [Ref. 7].

An evaluation of the data for each period enabled values to be found for To, T∞, Hw, U, qo, and B. Values for T were presented in surface temperature contour plots. Ambient sea surface temperature ($T\infty$) and the temperature of the boil (To) were taken directly from the surveys. The value for the current (U) was based on an analysis of the drogue tracks. These tracks showed highly variable currents in most cases. Complete reversal of current direction within a period of two to three hours was not uncommon. The currents appeared to have a high correlation with the tidal cycle. The atmospheric contribution (B) was computed using the heat budget, and the excess heat added by the outfall (qo) was estimated by taking the product of the temperature difference (To - $T\infty$) and the volume discharge. The depth of the temperature field (Hw) was determined from the actual thermal structure as measured by bathythermographs. There was a certain amount of subjectiveness in the selection of a single Hw for each period. In order to test the repeatability of selecting Hw, three individuals made independent observations. All observations were within 20 percent. To solve for Dx and Dy, it was assumed that diffusion is horizontally isotropic (i.e, Dx = Dy). This seems reasonable and any differentiation in the diffusion coefficient would be pure speculation. By substituting the coordinates and temperature from several locations on each surface temperature plot into the model solution, transcendental equations with Dx as the unknown were established. These transcendental equations were solved and the value of Dx which gave a "best fit" to the temperature field was chosen for each survey. By using an exponential approximation for large values of the Bessel function argument, a closed solution for Dx was possible. This first approximation of Dx was used as a check against the representative value chosen. Substituting Dx back into the model solution, a surface temperature field was generated for each survey period.

Comparisons of the generated fields and the actual measured fields may be seen in Figs. 6 through 12. The original data were presented in the engineering system of units (i.e., feet, ^{o}F). For ease in comparison, the generated temperature fields are presented in these same units. Table I lists the parameters used in the model and the values of Dx found.

TABLE I

DATA SUMMARY

Date	Dy m^2/sec	Hw m	U m/min	B x 10^4 cal/m^2/hr	qo cal/hr x 10^{11}
26 July	.87	3.00	4.1	3.92	8.0
27 July	1.39	3.60	2.0	3.06	5.6
16 August	1.95	3.00	4.8	3.06	8.8
17 August	1.17	2.20	5.8	3.06	8.0
28 August	1.53	3.60	5.0	2.86	11.8
4 October	2.08	3.00	3.0	2.86	7.7
16 February	.78	2.50	5.0	3.06	4.0

The differences between the observed temperature and the generated fields can be attributed mainly to irregular current patterns. The model is constrained to a steady state and only uniform velocity over the entire field is considered. Internal waves and upwelling or downwelling cause further irregularities in the temperature pattern. Figure 10 is a good example of this possibility. In all of the figures, the top border is the shoreward direction. The effect of the coast and shoaling may be seen in almost all of the figures. A further cause of differences may be natural oceanic turbulence. Roden [Ref. 19] concluded that random temperature fluctuations of .5^{o}F may be expected.

Roden's data, actually being derived from deep sea investigations, may in fact be conservative for nearshore regions where about $1^{o}F$ could be a significant temperature variation.

A further comparison was made to determine the relative importance of the heat budget contribution. Using the data for 27 July, the model was applied along the y-axis of the field both including and excluding the influence of the heat budget. Figure 13 is a plot of the temperature vs. distance along the y-axis for both of the above cases. The predicted temperatures are almost identical in the vicinity of the boil and differing slightly in the downstream direction; the curve representing the temperatures with the heat budget included are only a fraction of a degree less than those with the heat budget excluded. This is because the term involving B in the Bessel function argument is several orders of magnitude smaller than the velocity term in the argument. Thus, at least in this case, the heat loss term could be neglected without appreciable error in the results.

The effect of increasing or decreasing the velocity and the diffusion coefficient was examined. It was found that the areas enclosed by the isotherms varied inversely with the diffusion coefficient. The model appeared to be most sensitive to changes in the velocity (U). A decrease in velocity not only widened the field as would be expected, but also lengthened it. This is because the effect of the current is to more rapidly disperse the heat, decreasing the patch areas. From the relative importance of the two parameters in the exponential and Bessel function terms of the solution, one would expect an equal and opposite effect. However the presence of Dx in the constant term reverses the effect of the contribution from the exponential and Bessel function terms.

The effect of increasing the excess heat added by the effluent (qo) is obviously to increase the areas enclosed by the isotherms. Increasing the reference depth (Hw) would have the opposite effect. The contribution of Hw to the Bessel function term is negligible.

An examination of the fields generated by the model indicates that near the boil the isotherms are more circular and become more elongated as the distance increases. This is also observed in the surveyed temperature field and lends credence to the second boundary condition applied to the model solution.

An attempt was made to correlate the parameters used in the application of the model, particularly how Dx might functionally vary. Unfortunately no discernible correlations were found. It is felt that this is not a result of discrepancies in the model but reflects the lack of a sample of adequate size. The lowest diffusion coefficient was found for the coldest month and the largest diffusion coefficient was found for the warmest time of year in which the survey was conducted. This might indicate that Dx is a function of the thermal structure which is related to Hw and qo. However, there is notable exception to such a correlation. Another low diffusion coefficient was found for the 26 July survey during which time the winds were blowing at 18 knots and white caps were being generated. This was the most severe weather condition of all the surveys. This high input of turbulent energy would very definitely modify the thermal structure which in turn would effect Dx. Conversely, the sea was virtually smooth for the 16 February survey for which the lowest diffusion coefficient was found. More data will have to be taken and analyzed before meaningful correlations can be established.

V. CONCLUSIONS AND RECOMMENDATIONS

The dispersion model developed provides a method of predicting the temperature influence from a heated effluent along an open coast using known or assumed atmospheric and oceanic parameters. Diffusion coefficients were calculated in the calibration of the model as compared to the field data at Huntington Beach. The value of Dx varied from 0.78 - 2.08 m^2/sec.

An attempt was made to correlate the diffusion coefficient to the mean velocity, heat input and thermal structure. No correlation was discernible; this is attributed to the lack of a large enough sample.

The results of the application of the model tend to over predict the temperatures in the downstream direction and under predict the temperature in the upstream direction. This is evident in nearly all of the figures and can be attributed to the steady-state constraint on the model. Current direction fluctuations tend to spread heat out more evenly in both directions as indicated by the data. The contribution from the heat budget in this application was shown to be relatively insignificant and not critical to the results of the model. There may be situations where this term may be significant, therefore, for generality, it is recommended that the term be retained.

It is recommended that further research be conducted to refine the model presented in this study. Some possible considerations are: Addition of a third dimension, coupling jet dilution to the present model, incorporating the current induced by the volume discharge, and introducing time variability. Incorporating any of the above parameters will introduce new terms to the differential equation and make an analytical solution unlikely. More detailed and accurate surveys will also be necessary to calibrate these more complicated models.

A further recommended study would be the correlation of boil temperature to condenser discharge temperature. This could be done by taking temperatures of the boils at a number of different power stations hopefully with a wide range of outfall depths, outfall volumes and condenser discharge temperatures. An analysis of the study could provide an empirical formula for the boil temperature as a function of condenser discharge temperature, outfall depth, outfall volume and outfall diameter. This could be incorporated in the above model and would allow an effluent field prediction starting at the point of discharge.

TABLE II

Data for Computing Solar Altitude

(from James)

DATE		SUN'S (°) DECLINATION	DURATION OF DAYLIGHT (HRS) 20	30	40	50	60	Lat(N)
January	1	-23	11	10	9	8	6	
	15	-21	11	10	10	9	7	
February	1	-17	11	11	10	9	8	
	15	-13	11	11	11	10	9	
March	1	-9	12	11	11	11	10	
	15	-3	12	12	12	12	12	
April	1	3	12	12	13	13	13	
	15	9	13	13	13	14	14	
May	1	14	13	13	14	15	16	
	15	19	13	14	14	15	17	
June	1	22	13	14	15	16	18	
	15	23	13	14	15	16	19	
July	1	23	13	14	15	16	19	
	15	21	13	14	15	16	18	
August	1	17	13	14	14	15	17	
	15	13	13	13	14	14	16	
September	1	8	13	13	13	14	14	
	15	3	12	12	13	13	13	
October	1	-3	12	12	12	12	12	
	15	-9	12	11	11	11	10	
November	1	-15	11	11	11	10	9	
	15	-19	11	11	10	9	8	
December	1	-22	11	10	10	9	7	
	15	-23	11	10	9	8	6	

TABLE III

Lumb's Cloud Classifications for Computing Insolation

(From James)

CATEGORY	DESCRIPTION
1	Virtually clear sky, less than two eights coverage.
2	Well-broken low clouds with little or no medium or high cloud (three to five eighths).
3	Six to eight eighths of cirrus (not cirrostratus).
4	Thin layers of altocumulus, six to eight eighths.
5	Veil of cirrostratus over whole sky with up to four eighths low clouds.
6	Seven or eight eighths of stratocumulus without rain, with or without some cumulus and little or no medium clouds.
7	Thick altostratus six to eight eighths, with or without layers of stratocumulus beneath some rain.
8	Thick layers of stratus and stratocumulus, overcast, including drizzle.
9	Thick layers of nimbostratus, overcast, also include medium clouds, and rain.

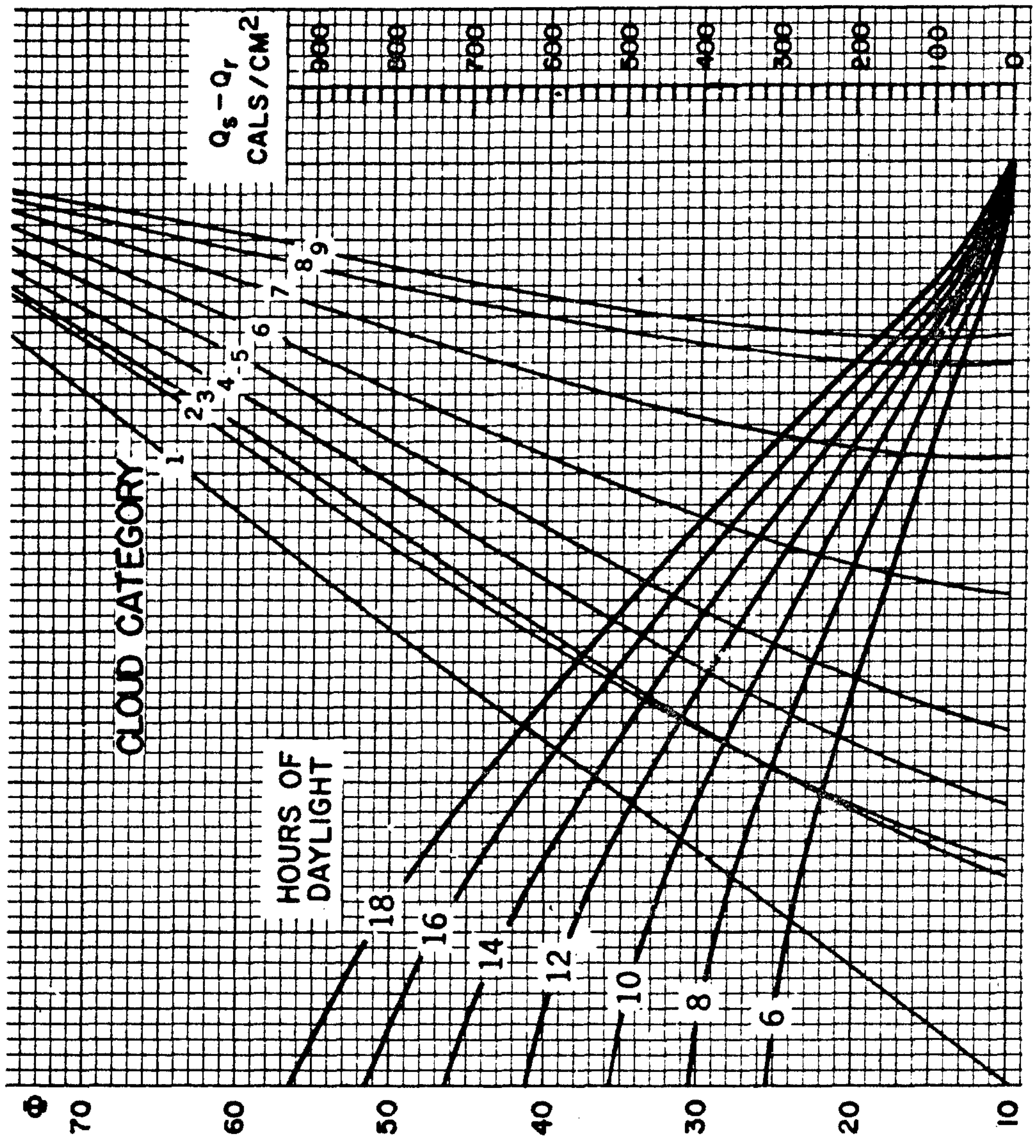


FIGURE 1

Total Daily Effective Insolation (Q_S - Q_r)

(from James)

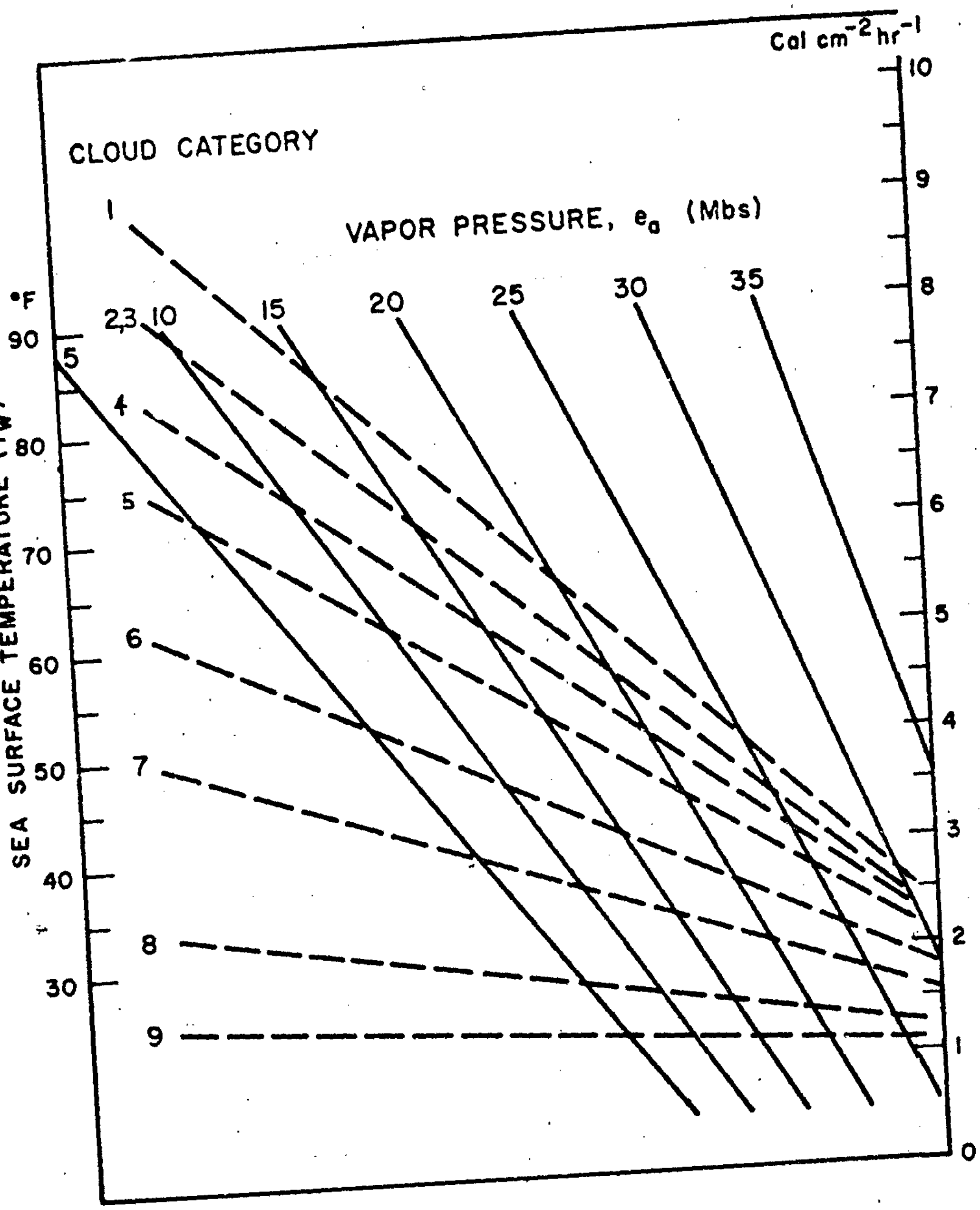


FIGURE 2
Effective Back Radiation (Q_b)
(from James)

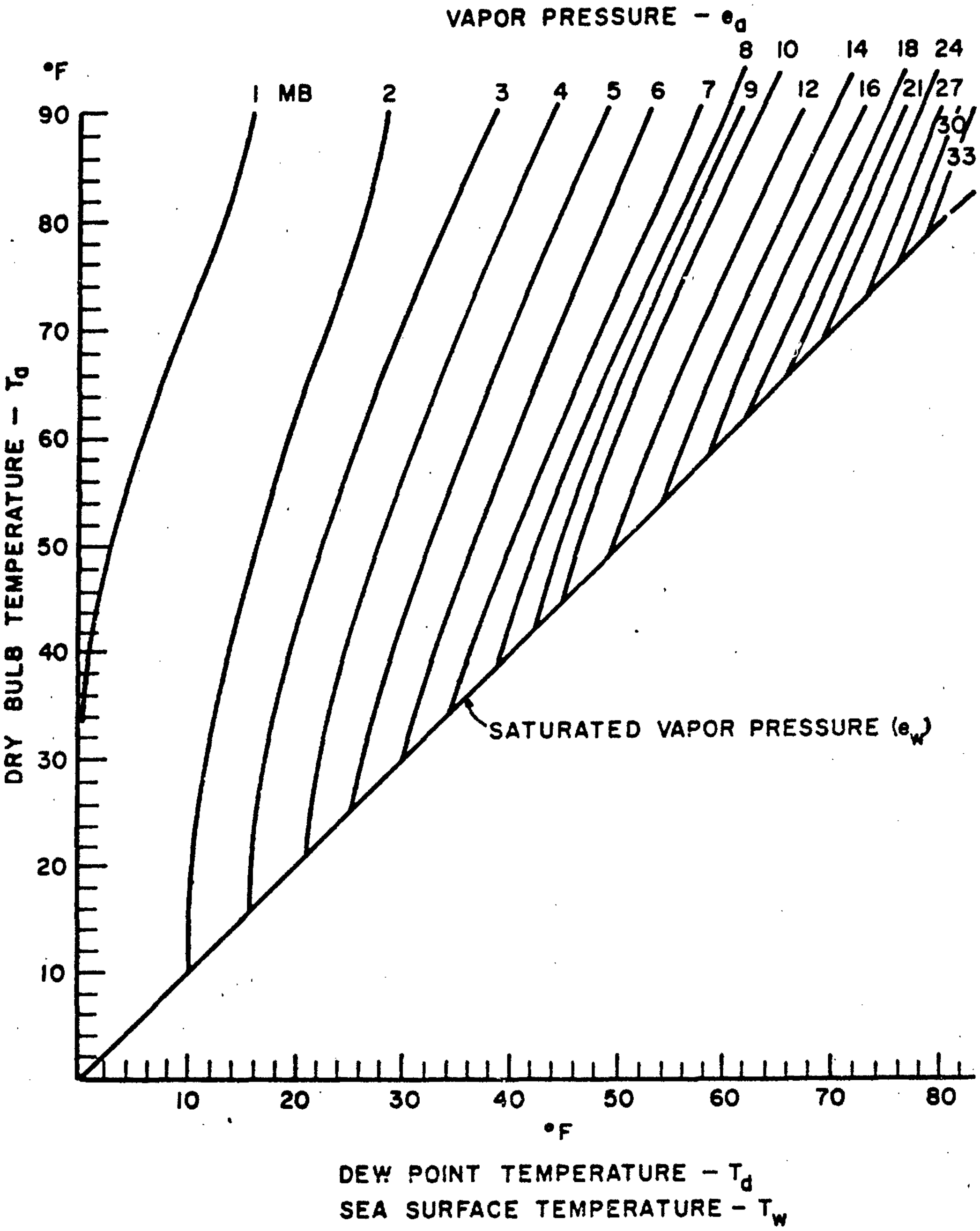


FIGURE 3

Vapor Pressure Nomograph

(from James)

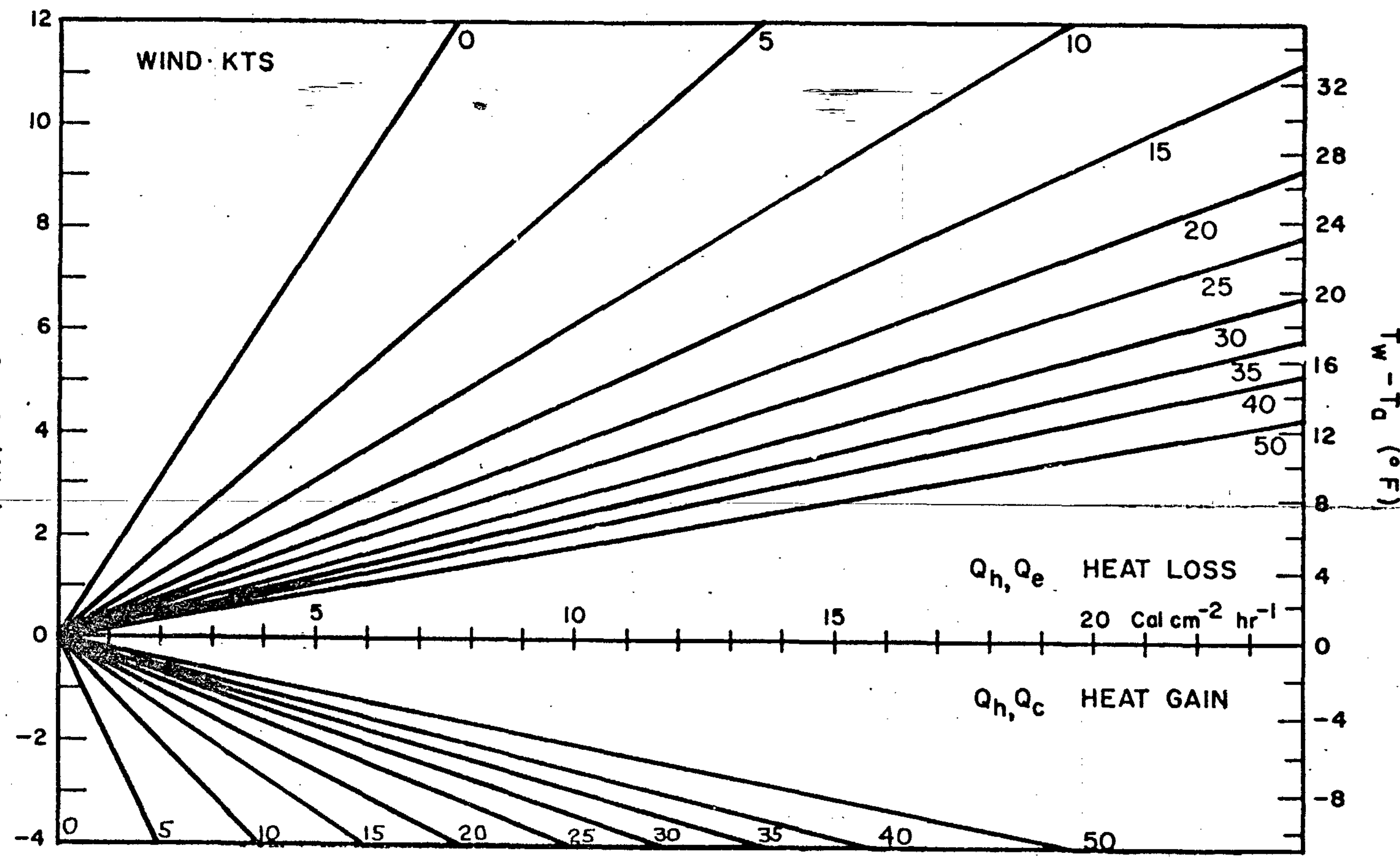


FIGURE 4

Latent Heat of Evaporation and Condensation and Sensible Heat Transfer

(from James)

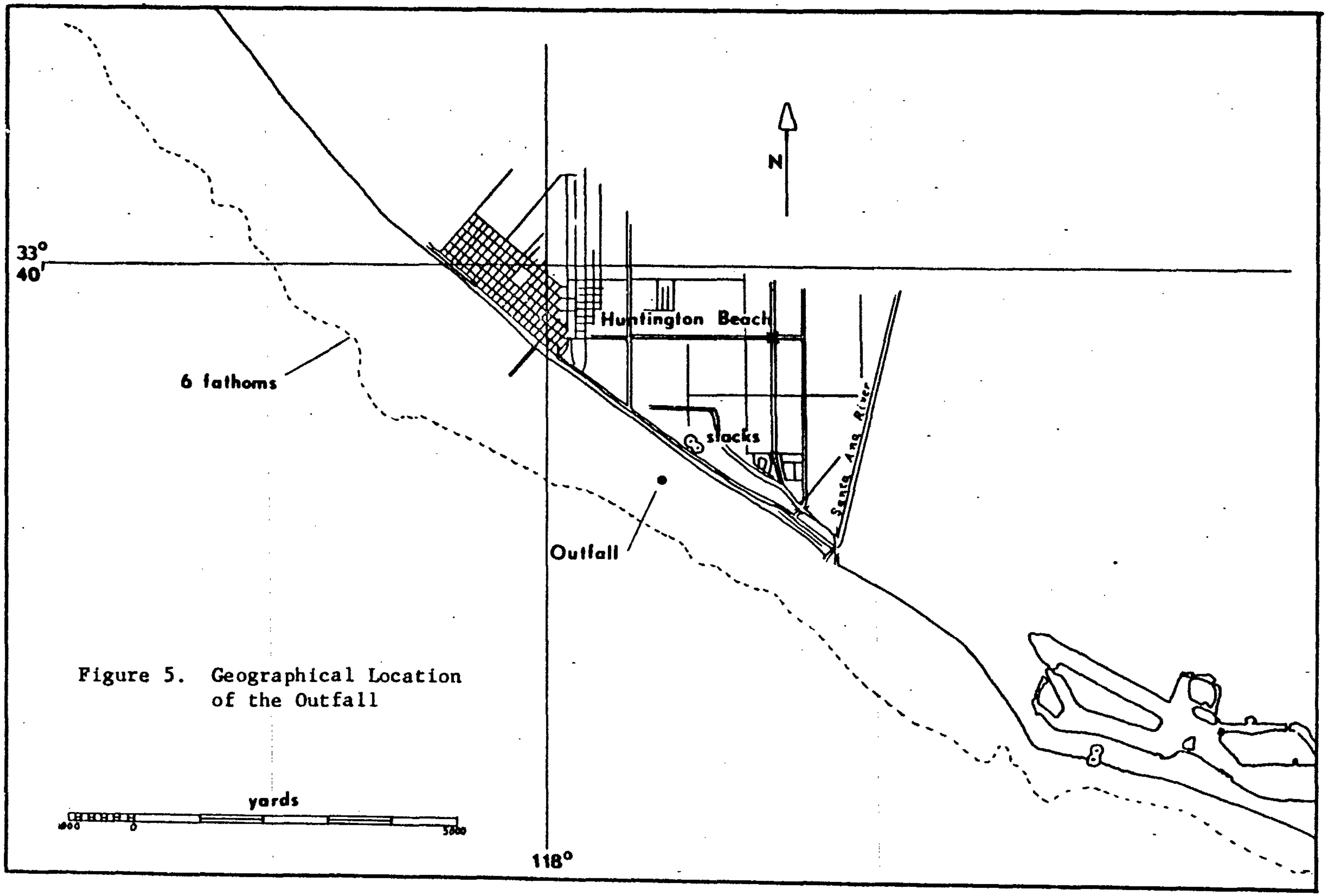
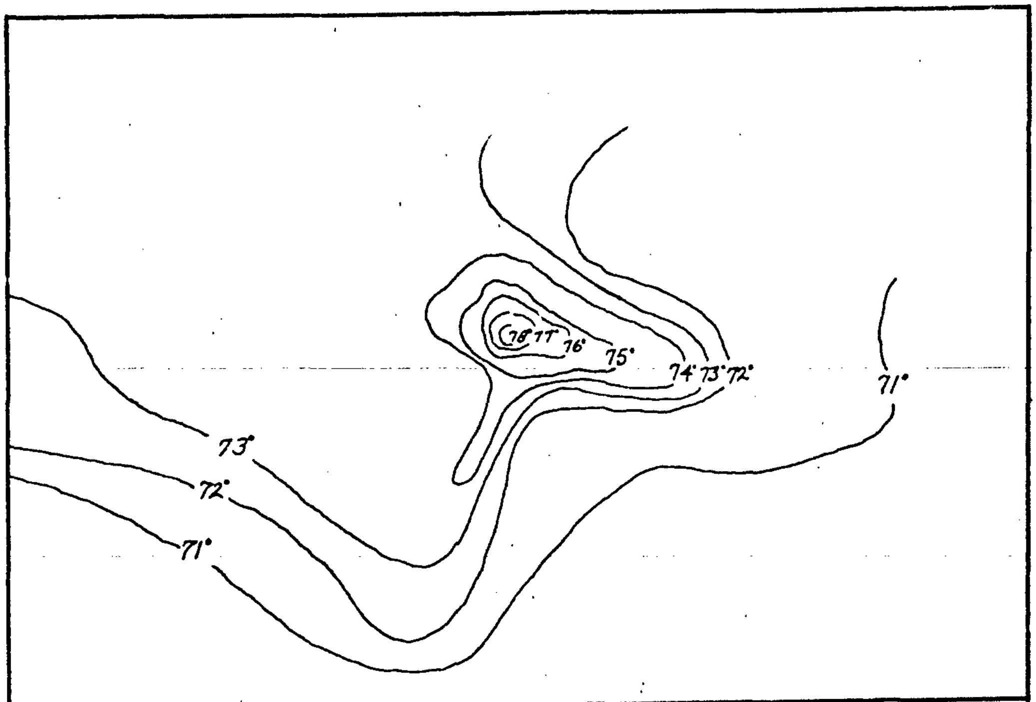


Figure 5. Geographical Location of the Outfall



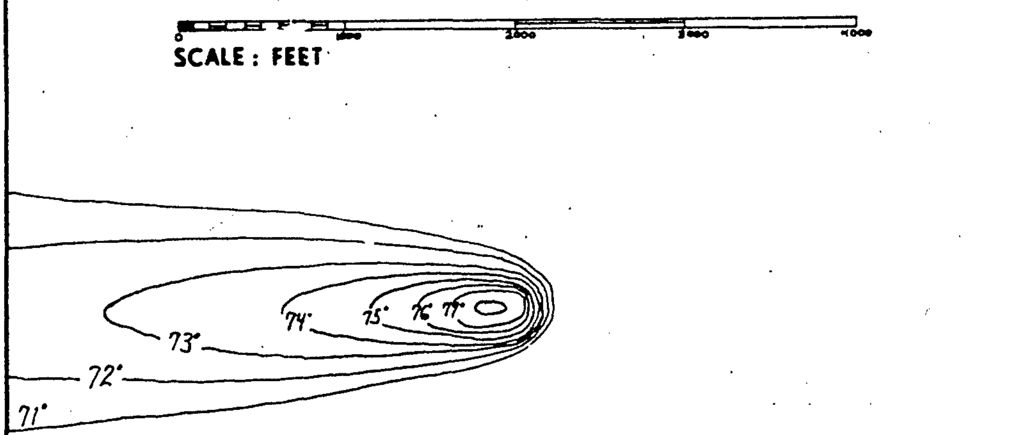


FIGURE : 6

SURFACE TEMPERATURES **26 JULY 1963**

Dx =.87 m^2/sec

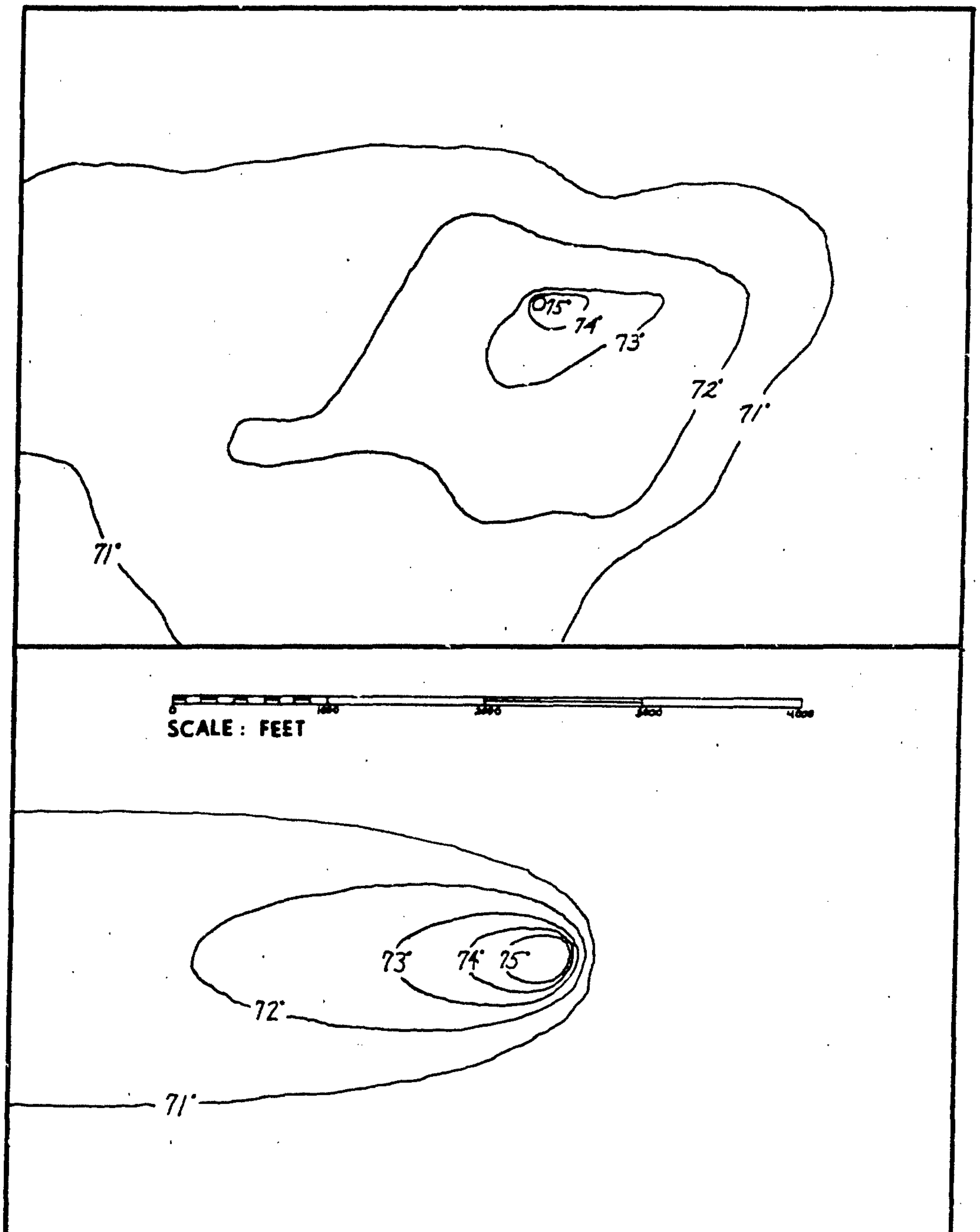


FIGURE: 7

SURFACE TEMPERATURES 27 JULY 1963

$D_x = 1.39\ m^2/sec$

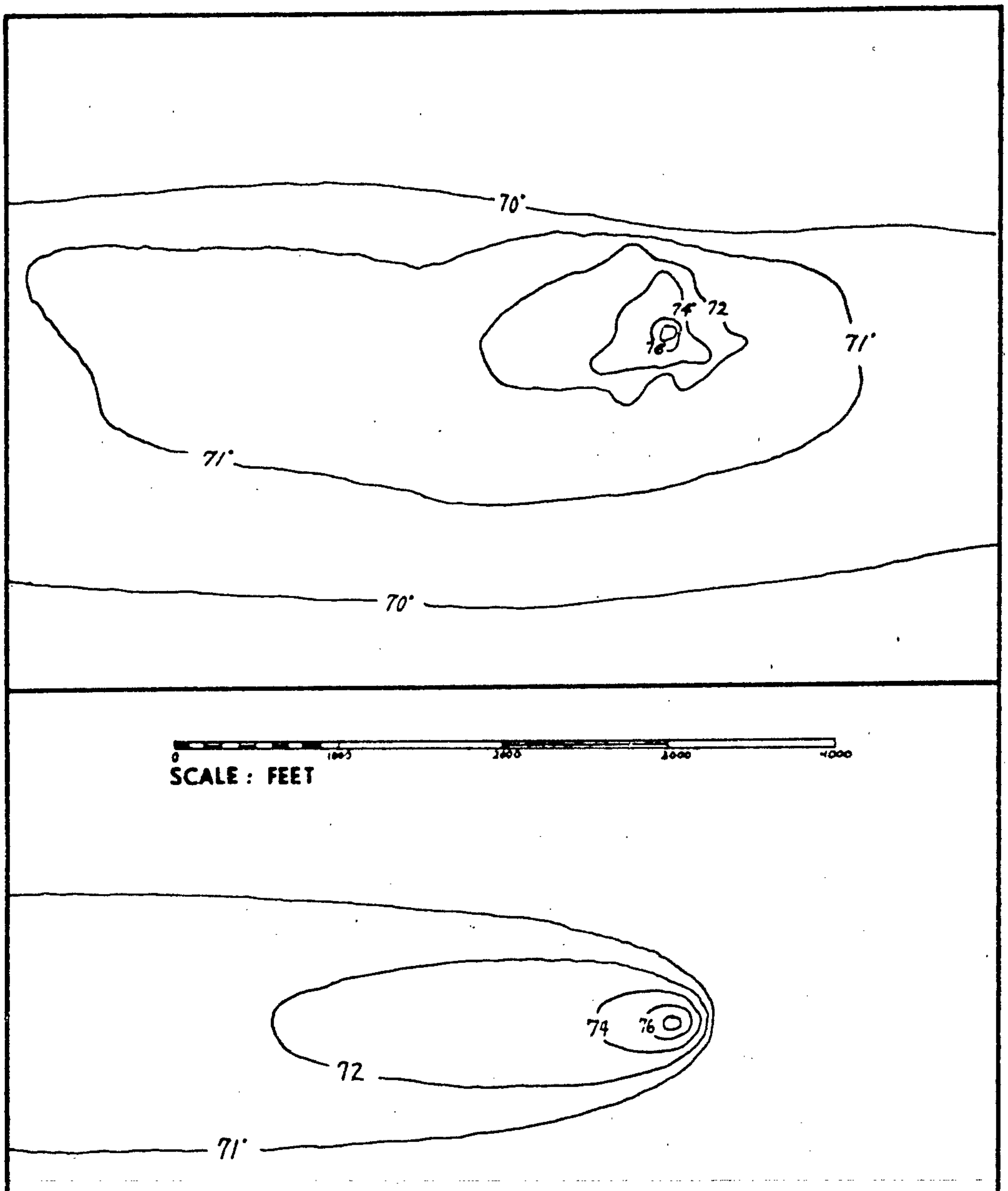


FIGURE : 8

SURFACE TEMPERATURES 16 AUGUST 1963

Dx = 1.95 m^2/ sec

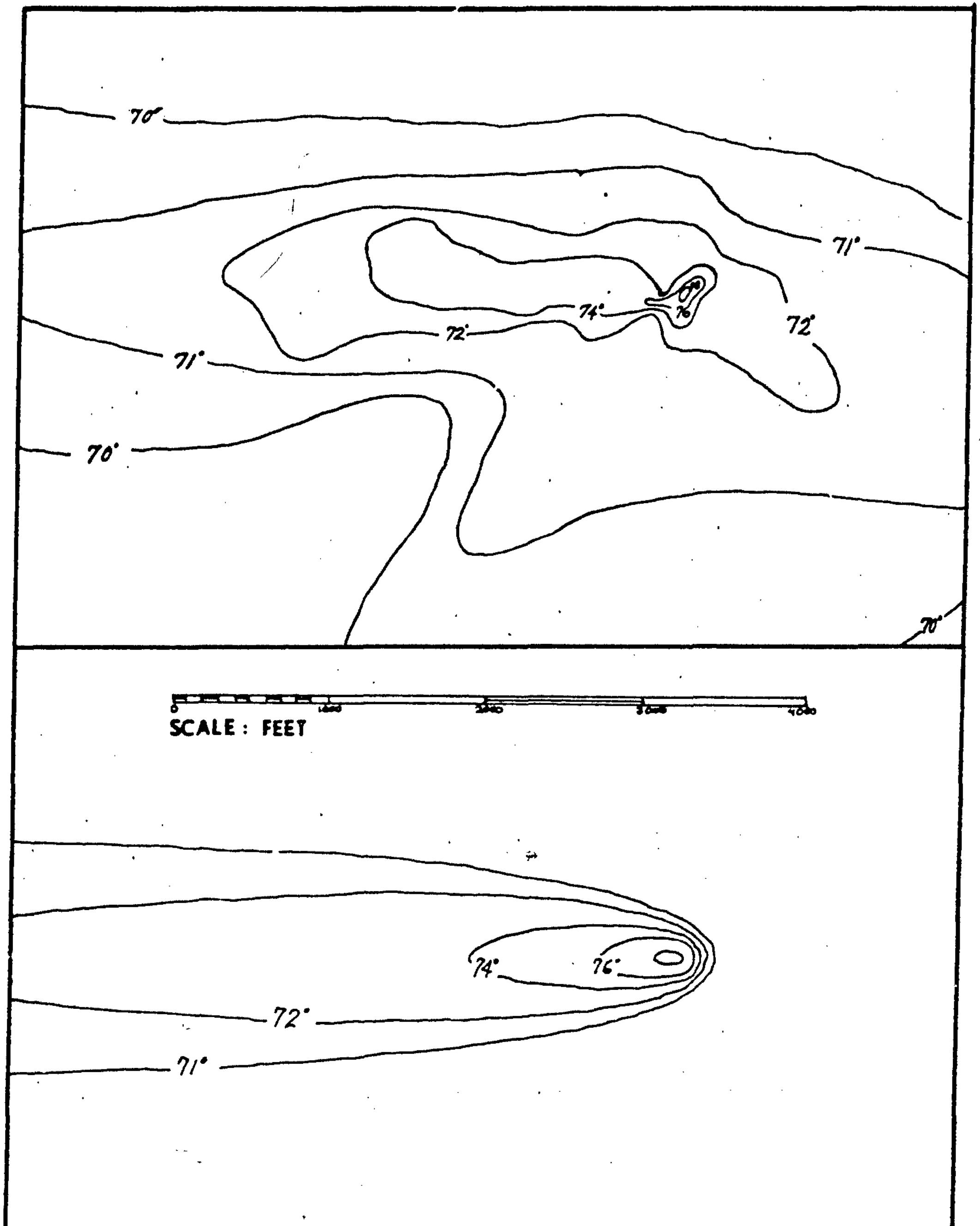


FIGURE : 9

SURFACE TEMPERATURES 17 AUGUST 1963

$D_x = 1.17\ m^2/sec$

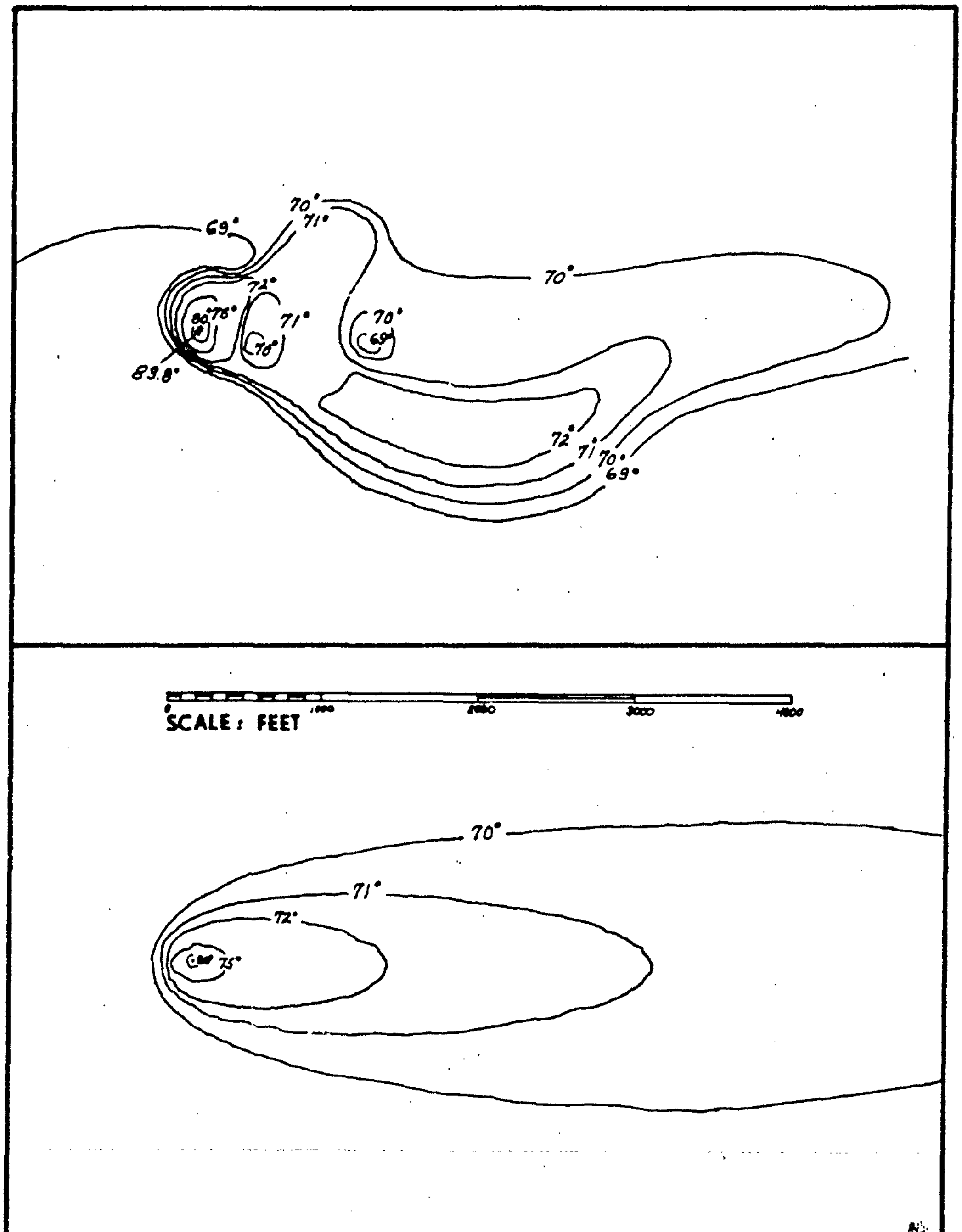


FIGURE: 10

SURFACE TEMPERATURES
28 AUGUST 1963
Dx = 1.53 m^2/sec

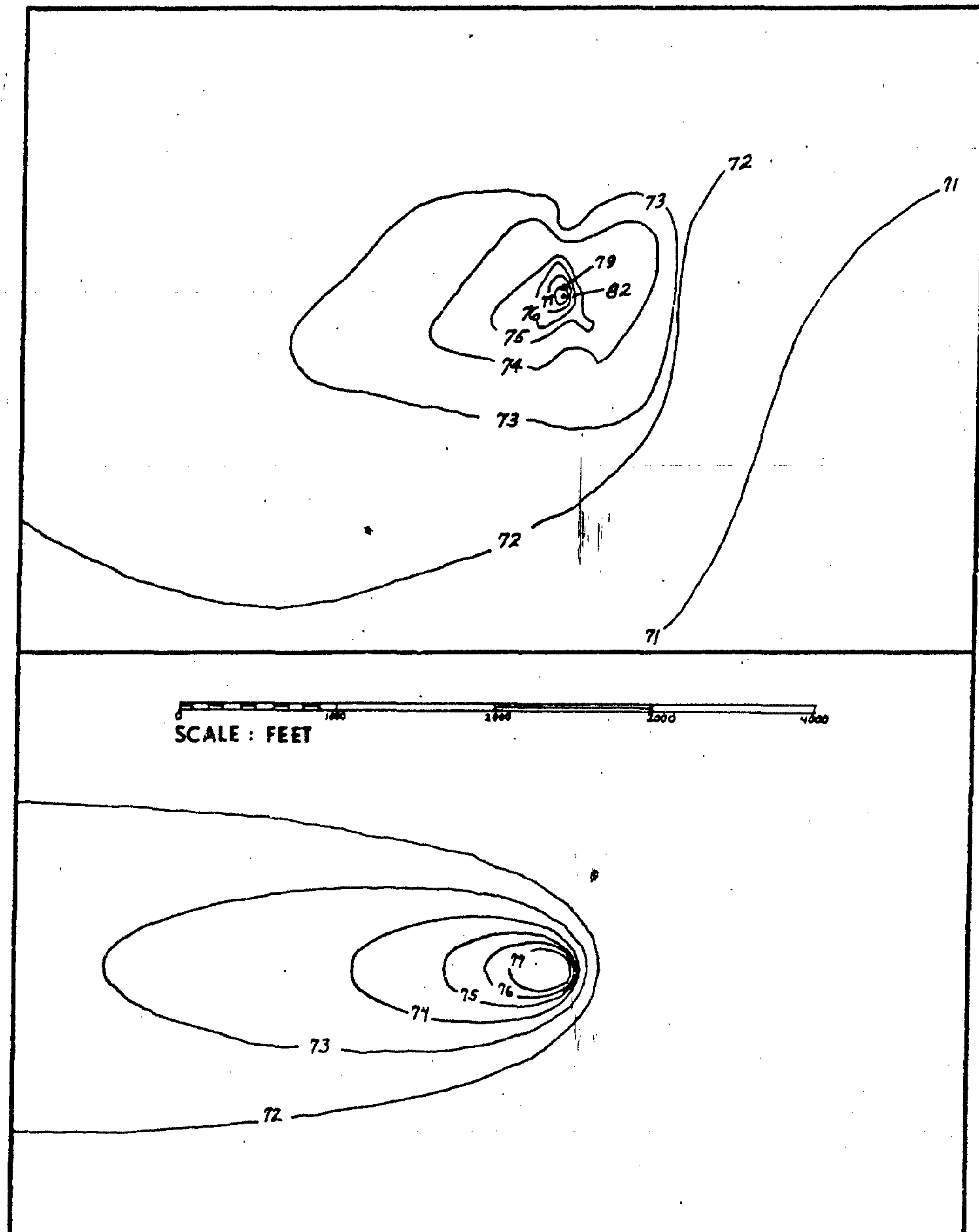


FIGURE : 11

SURFACE TEMPERATURE 4 OCTOBER 1963

Dx = 2.08 m^2/sec

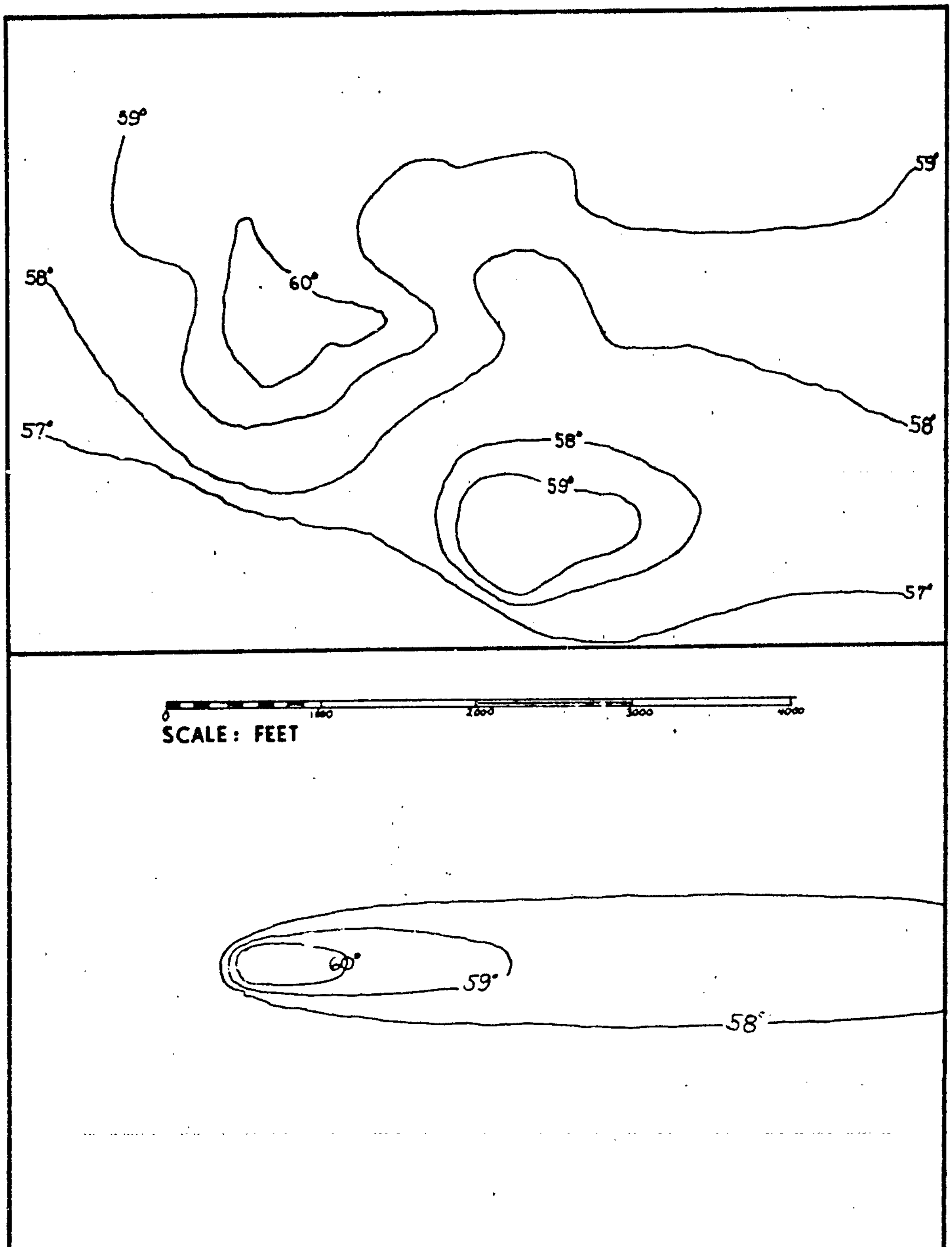


FIGURE: 12

SURFACE TEMPERATURES 16 FEBRUARY 1965

$D_x = .78\ m^2/sec$

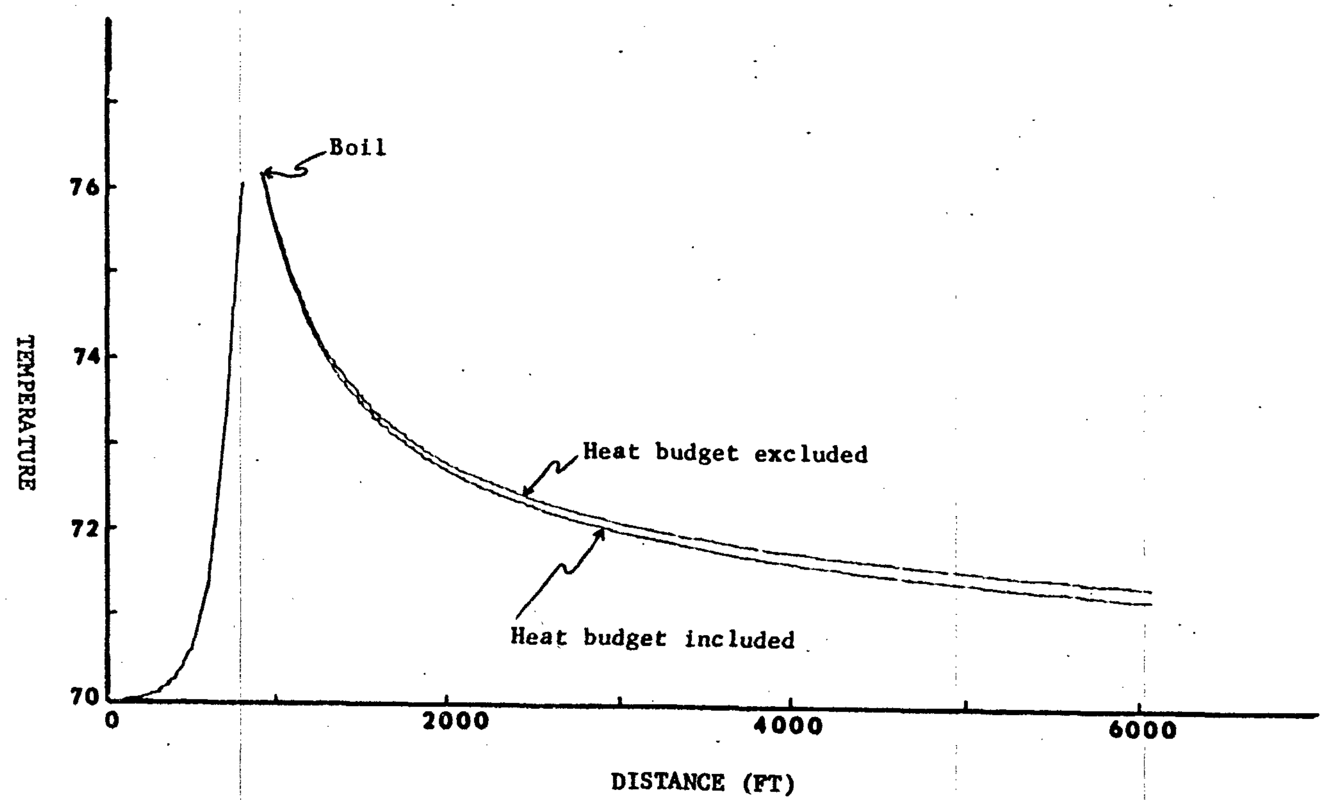


Figure 13. Comparison of the Significance of the Heat Budget

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13. ABSTRACT

A mathematical model is developed for dispersion of a heated effluent from an ocean outfall. Input parameters include atmospheric and oceanic conditions and discharge characteristics. The model solves the steady-state, two-dimensional differential equation for non-conservative diffusion of heat in a moving fluid. The solution is calibrated and verified using data from surveys conducted at the Southern California Edison Company power plant at Huntington Beach, California. Temperature fields predicted by the model are compared with the actual fields for seven different surveys. These comparisons indicate that the model can be used to predict the large scale influence of the outfall on the local ocean environment.

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